ANALAYIS OF INTERIM THERMAL STRESS LIMITS FOR A PORTABLE RECOMPRESSION SYSTEM

by

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NAVAL SUBMARINE MEDICAL RESEARCH LABORATORY
REPORT NUMBER 904

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SUMMARY PAGE

THE PROBLEM

A recent evaluation of a portable recompression system (PRS) at the Naval Submarine Medical Research Laboratory showed that the most serious problem observed was that of thermal stress. It was recognized that this thermal stress might produce a significant safety problem and may compromise the adequacy of treatment in a tropical climate, where temperatures can be 5-10°C (9-18°F) higher than the conditions under which the chamber was evaluated. An analysis of the thermal stress load that may be placed upon a diver being treated for decompression sickness in the PRS and his ability to transfer heat to the environment was therefore conducted.

FINDINGS

The heat stress expected for various ambient air temperatures, assuming 100% RH, is as follows: 25°C (77°F) and below - no heat stress expected, diver comfortable; 26-29°C (78-84°F) - diver will sweat profusely and be uncomfortable toward high end of zone, but stress should be entirely compensable; 29°C (85°F) - diver will be very uncomfortable and heart rate and rectal temperature will rise to a new steady state; 30-31°C (86-87°F) - diver unable to compensate for heat stress and rectal temperature and heart rate will rise continuously until collapse at about 6 hours; 31°C (88°F) and above - time to collapse is considerably shortened being 2 hours at 31-32°C (88-90°F) and less than 1 hour at 34°C (94°C).

APPLICATION

These interim thermal limits based on sound physical principles and related empirical studies will serve as guidelines to PRS operators in the field while awaiting human-tested limits now under study.

ADMINISTRATIVE INFORMATION

This investigation was conducted while the author was attached to the John B. Pierce Foundation Laboratory, New Haven, Connecticut in a training billet sponsored by the Health Sciences and Education Training Command.

The manuscript was submitted for review on 12 July 1979 and approved for publication on 7 August 1979. It has been designated as NavSubMedRschLab Rpt. No. 904.

PUBLISHED BY THE NAVAL SUBMARINE MEDICAL RESEARCH LABORATORY

ABSTRACT

An analysis was conducted of the thermal heat loads expected and the diver's ability to regulate his internal temperature during use of the Navy's one-man portable recompression system (PRS). Using conventional heat balance and heat exchange relationships, a graph was constructed, from which the heat load on the diver could be predicted knowing the ambient air temperature and humidity. Based on the assumption that relative humidity will be near 100% and introducing a safety margin by conducting the analysis as if the total decompression treatment took place at 4 atmospheres absolute, the heat stress expected for various ambient air temperature is as follows: 25°C(77°F) and below - no heat stress expected, diver comfortable; 26-29°C (78-84°F) - diver will sweat profusely and be uncomfortable toward high end of zone, but stress should be entirely compensable; 29°C (85°F) - diver will be very uncomfortable and heart rate and rectal temperature will rise to a new steady state; 30-31°(86-87°F) - diver unable to compensate for heat stress and rectal temperature and heart rate will rise continuously until collapse at about 6 hours; 31°C(88°F) and above: time to collapse is considerably shortened being 2 hours at 31-32°C(88-90°F) and less than 1 hour at 34°C(94°F).

A recent evaluation of a portable recompression system (PRS) at the Naval Submarine Medical Research Laboratory showed that the most serious problem observed was that of thermal stress (14). Because of lack of provision for temperature and humidity controls, adequate environmental adjustments were unable to be made to prevent considerable thermal discomfort to the subjects. Upon completion of the tests, it was recognized that this thermal stress might produce a significant safety problem and may compromise the adequacy of treatment in a tropical climate, where temperature can be 5-10°C (9-18°F) higher than the conditions under which the chamber was evaluated. Additionally, it was also recognized that predictions of thermal stress under these conditions would have to be based on theory only, since no human laboratory experimentation under such conditions has been performed. Especially lacking in this regard was the effect of pressure on man's ability to dissipate heat by evaporative mechanisms. The following is an analysis of the thermal stress loads that may be placed upon a diver being treated for decompression sickness in the PRS and his ability to transfer the heat to the environment. From this analysis, interim thermal stress limits are developed for use as guidelines by the treating physician or technician.

THEORY

The metabolic heat equation for the body may be written to express the amount of heat (in watts per square meter of skin surface - Wm^{-2}) transferred to the skin as follows:

$$H_{sk} = M - E_{res} - C_{res} - (W) - S \qquad \text{(Eq. 1)}$$

where

M = the energy metabolism (as derived from O_2 consumption) ..... Wm^{-2}

$$E_{res} = 0.0023\ M\ (44 - P_a)\ .....Wm^{-2} \qquad (6) \qquad \text{(Eq. 2)}$$

heat exchange due to evaporation from the respiratory tract (P_a = ambient water vapor pressure in Torr).

$$C_{res} = 0.0014\ M(34 - T_a)\ .....Wm^{-2} \qquad (6) \qquad \text{(Eq. 3)}$$

heat exchange due to convection from the respiratory tract (T_a = ambient temperature in °C).

$$W = \text{Work accomplished } .....Wm^{-2} \qquad \text{(Eq. 4)}$$

$$S = \text{Rate of body heat stored } .....Wm^{-2} \qquad \text{(Eq. 5)}$$

The sensible heat exchange between the skin surface and the environment is governed by the physical laws of radiation, convection, and evaporation (conduction is usually not considered separately and is considered part of the convective-radiative exchange). Radiation exchange is expressed by the heat trasnfer coefficient, h_r, and follows the relation

$$h_r = 4 \cdot (0.72) \cdot (5.67 \times 10^{-8}) [(T_o + T_{surf})/2 + 273.2]^3$$

where .....$Wm^{-2 o}C^{-1}$ (Eq. 6)

0.72 = effective radiative DuBois surface

5.67×10^{-8} = Stefan-Boltzmann constant

T_o = operative temperature (for this analysis $T_o = T_a = T_r$ and T_r is the mean radiant temperature).

T_{surf} = body surface temperature expressed as a mean skin temperature ($\overline{T}_{sk}$) .....^oC

Convective exchange is expressed by the convective heat coefficient (h_c) and depends only upon air velocity and ambient pressure. While numerous expressions have been determined empirically for various-shaped models and body positions, the following relation will be used in this analysis (assuming air flow to be just above still condition)

$$h_c = 8.6\ [v \cdot P_B]^{.53} \quad .....Wm^{-2}C^{-1} \quad (17) \qquad \text{(Eq. 7)}$$

where

v = velocity of air in meters per second (m/s).

P_B = barometric pressure in atmospheres absolute (ATA).

Evaporative exchange is expressed by the evaporative heat exchange coefficient (h_r) and follows the relation

$$h_e = LR\ h_c \quad .....Wm^{-2}C^{-1} \qquad \text{(Eq. 8)}$$

where

$$LR \sim (D/k)^{0.67}/(\rho \cdot cp)^{0.33} \qquad \text{(Eq. 9)}$$

and

D = mass diffusivity of water in the gas.

k = thermal conductivity of the gas

ρ = density of the gas

cp = heat capacity of the gas

The Lewis Relation (LR) for air at one atmosphere is constant and equals 2.2; thus

$$h_e = 2.2\ h_c \quad .....Wm^{-2}C^{-1} \qquad \text{(Eq. 10)}$$

The above exchange coefficients (h_r, h_c, and h_e) are all modified by clothing. These modifications will not be considered in this analysis since it is assumed that the treated diver will be nude or wearing only swim trunks.

Heat exchange between the skin surface and the environment can now be expressed in terms of radiative and convective losses (the sensible losses) and the evaporative losses (the insensible losses). The sensible and insensible losses are governed by the differences in mean skin temperature and ambient temperature, and saturated skin vapor pressure and ambient vapor pressure respectively, so that

$$H_{sk} = (h_r+h_c)(\bar{T}_{sk} - \bar{T}_o) + wh_e(P_{s,sk} - P_a) \quad .....Wm^{-2} \qquad \text{(Eq. 11)}$$

where

w = skin wettedness (dimensionless)

$P_{s,sk}$ = saturated skin vapor pressure .....Torr

P_a = ambient vapor pressure .....Torr

Equation 11 may be plotted on a psychrometric chart (temperature on the abscissa and water vapor pressure on the ordinate) and will describe a straight line (18) that passes through the two points $[P_{s,sk} - H_{sk}/(h_r + h_c)]$ and (P_a, T_o) with a negative slope of $[(h_r + h_c)/wh_e]$.

It has been determined (7, 11, 16) that the threshold for sweating occurs when $w = 0.6$ and $\bar{T}_{sk}$ 34°C. Toward the cold, heat loss by evaporation is governed by diffusional losses only. Between $w = .06$ and $w = 1.0$, increasing amounts of sweat will appear on the skin until it is fully wetted at $w = 1$ and $\bar{T}_{sk} = 36.5$°C (7, 11, 16). Heat exchange by evaporation at $w = 1$ is considered maximum (E_{max}) and is described by the relation

$$E_{max} = LR \cdot h_c \cdot (P_{s,sk} - P_a) \quad .....Wm^{-2} \qquad \text{(Eq. 12)}$$

Thus, body heat exchange is regulated by evaporation for w values of 0.06 to 1.0. This is considered a compensatory zone where body temperature may rise, but will eventually reach a new steady state (11, 12, 16). Once a wettedness of 1 is reached, the body can longer compensate by evaporation for increasing heat loads, heat is progressively stored, and thus body temperature rises. An example of these relationships is plotted on a psychrometric chart in Figure 1. This chart shows how the zone of evaporative regulation is affected by different air velocities. In this analysis the subject is wearing clothing with an effective insulation of 0.6 clo units (1 clo = 0.155 m^2°CW^{-1}).

Effects of Pressure on Heat Exchange

The convective heat transfer coefficient (h_c), as shown in eq. 7, is dependent on air movement and pressure and increases as approximately the square root of the pressure. The evaporative heat coefficient is dependent on both air movement, because of its h_c component, and on pressure because of its relationship to both h_c and the Lewis Relation (LR). Since mass diffusivity decreases proportionately with pressure and density increases proportionately with pressure, LR (eq. 9) varies inversely with P_B and for air LR = $2.2/P_B$.

The key to any analysis of heat exchange as a function of pressure lies in the magnitude of changes in h_c and h_e. Thus, since h_e decreases as the inverse of pressure and h_c increases as the square root of pressure, when the gas composition and air velocity remain constant, heat exchange by evaporation is affected to a greater extent than heat exchange by convection. Because diving is generally done in cool or cold water (relative to body temperature) and because deep diving uses helium oxygen mixtures for the compression gas, diving has been associated with the concept of increased heat loss. This is undeniably the case, since on the cool side of comfort heat loss is predominantly governed by convection and, not only does h_c increase with pressure, but h_c for helium is nearly two times that of air. On the warm side of comfort, however, heat loss is predominantly governed by evaporation, with convective losses assuming a lesser and lesser role as T_a increases (v is constant). Respiratory heat loss via evaporation is constant with increasing pressure, but respiratory convective exchange is altered proportionately with pressure.

Analysis of Heat Transfer in the Portable Recompression System (PRS)

An analysis of heat exchange in the portable recompression system based on the system developed by Nishi and Gagge (18) is now given. This analysis follows the basic concepts and would have reached the same conclusions if the heat exchange concepts presented by Wissler (24) were used. The Nishi-Gagge format is used because the terminology and system of symbols are consistent with that approved by the subcommittee on thermal physiology of the Nomenclature Committee of the International Union of Physiological Sciences (8). In addition, a number of published reports on heat exchange have appeared in the literature using this format (9, 18, 10) and thus afford a ready comparison of the specific analysis presented here with the more general analyses of heat exchange discussed in these reports.

The following analysis will determine the points (T_a, P_a) at which, for any given pressure of 1-4 ATA, the body can no longer compensate for its given heat load and rectal temperature and heart rate will continue to rise as long as the given conditions persist, culminating in complete collapse. For each ATA, these points describe a straight line and are defined in Figure 2 by the w= 1 lines. Included in the analysis are lines for w = 0.06 at 1 and 4 ATA. At points where w = 0.06, regulation of heat exchange by sweating begins. In this sweating zone (w = 0.06 to w = 1.0), also called the zone of evaporative regulation or compensable zone, body temperature and heart rate will increase, but will reach some new steady state, as discussed previously. Around a w = 0.6 to 0.7 the environment becomes uncomfortable (7, 9, 10, 11, 12, 16); while the body may compensate completely for the heat load, if exposure times are lengthy (hours) then problems of water balance may ensue (2, 4, 12, 15, 21). A line for w = 0.7 is drawn and the area between w = 0.07 and 1.0 may be considered as a caution zone where severe heat strain is likely to develop.

The appropriate constants and variables needed to fulfill equation 1 and 11 and thus to determine the lines on Figure 2 are given in Table 1.

It should be readily apparent from Figure 2 that 1) the compensable zone for body heat exchange is considerably reduced at increased pressures and 2) critical temperatures that indicate the limit of body compensation are not widely different for pressures of 1-4 ATA at high humidities, but are considerably different at low humidities.

The pie-shaped area bordered by w = 0.06 and w = 1.0 for 4 ATA in Figure 2, has been expanded and replotted in Figure 3. If chamber temperature and humidity are known or can be estimated, the chamber operator may use this chart to determine in what heat exchange zone the diver will be placed and, along with Appendix B, can determine the possible consequences of doing such. In addition, by use of the "hours lines" to reach a body temperature of 39.6 plotted on the graph, the operator will be able to determine, for any given condition beyond the w= 1 line, the approximate time of imminent collapse of the diver from heat stroke. These lines were determined by calculating heat storage (S) from equation 1, determining the rate of deep body temperature change from

$$\Delta T_b/\Delta t = S \times [1.8/(.97 \cdot 70)] \qquad \text{(Eq. 13)}$$

where

$\Delta T_b/\Delta t$ = the change in deep body temperature per change in time ..... $\Delta C/\Delta h$

1.8 = DuBois surface area of a "standard" man .....m^2

.97 = Body specific heat .....$W \cdot h \cdot {}^oC^{-1}$ kg

70 = Body mass of a "standard man" .....kg

and then dividing 2.6^{o}C [assuming deep body temperature to start at 37.9 (11)] by $\Delta T_b/\Delta h$ to obtain "hours" to reach 39.6^{o}C. Numerous values for deep body temperature limits exist in the literature and range from 38.0 for the civilian work force (20) to 38.5 for divers (23) to 38.9 for shipboard workers' limits (5), and to 39-40 for some experimental protocols (13, 3, 11, 25). The probablility of divers sustaining heat stroke is greater than 1 in 100 if their rectal temperatures reach 39.6 under these environmental conditions (25). Times to reach this deep body temperature are given only as guidelines and do not constitute a recommendation that environmental conditions that are predicted to produce a deep body temperature of 39.6 or less are safe or constitute a no-risk situation with regard to heat stress.

The chart recommended for operational use is based upon a heat exchange analysis for conditions at 4 ATA only. The treatment tables likely to be used with the PRS compress to an initial pressure of 4 ATA (Table 1A)* or 3 ATA (Table 5 and 6) and then decompress in a stepwise fashion to 1 ATA (22). It is recognized, therefore, that this analysis overestimates the heat stress for any given condition of chamber temperature

*Table 1A, Table 5 and 6 here and henceforth refer to Navy Diving Tables (22).

and humidity. While it was the intent to purposely overestimate the stress since these limits await experimental confirmation and a wide safety margin was therefore felt necessary, the following abbreviated analysis is presented to give an estimate of the degree of overestimation.

Temperature and humidity combinations were located on the "4 hour" line of the 4 ATA chart for humidities of 100, 90, 80, and 50%. If treatment took place for the total treatment table at 4 ATA, deep body temperature would reach 39.6°C in 4 hours for these temperature and humidity combinations. If, however, decompression to less than initial treatment pressure takes place progressively, as it would normally during the use of any treatment table (Table 1A is used for example here) final body temperatures at the end of the 380 min. treatment (6.3 h) is computed to be 40.5, 39.4, 38.6, and 37.8 at 100, 90, 80, and 50% RH, respectively (Table 2). It may be stated therefore that the chart is a good predictor for the very high humidities, but may substantially overestimate heat stress at the middle and lower humidities. Assuming the humidity as a worst case to be 90-100% in the chamber, the technician can use Table 3 as a guide for prediction of the thermal stress he should expect in the field.

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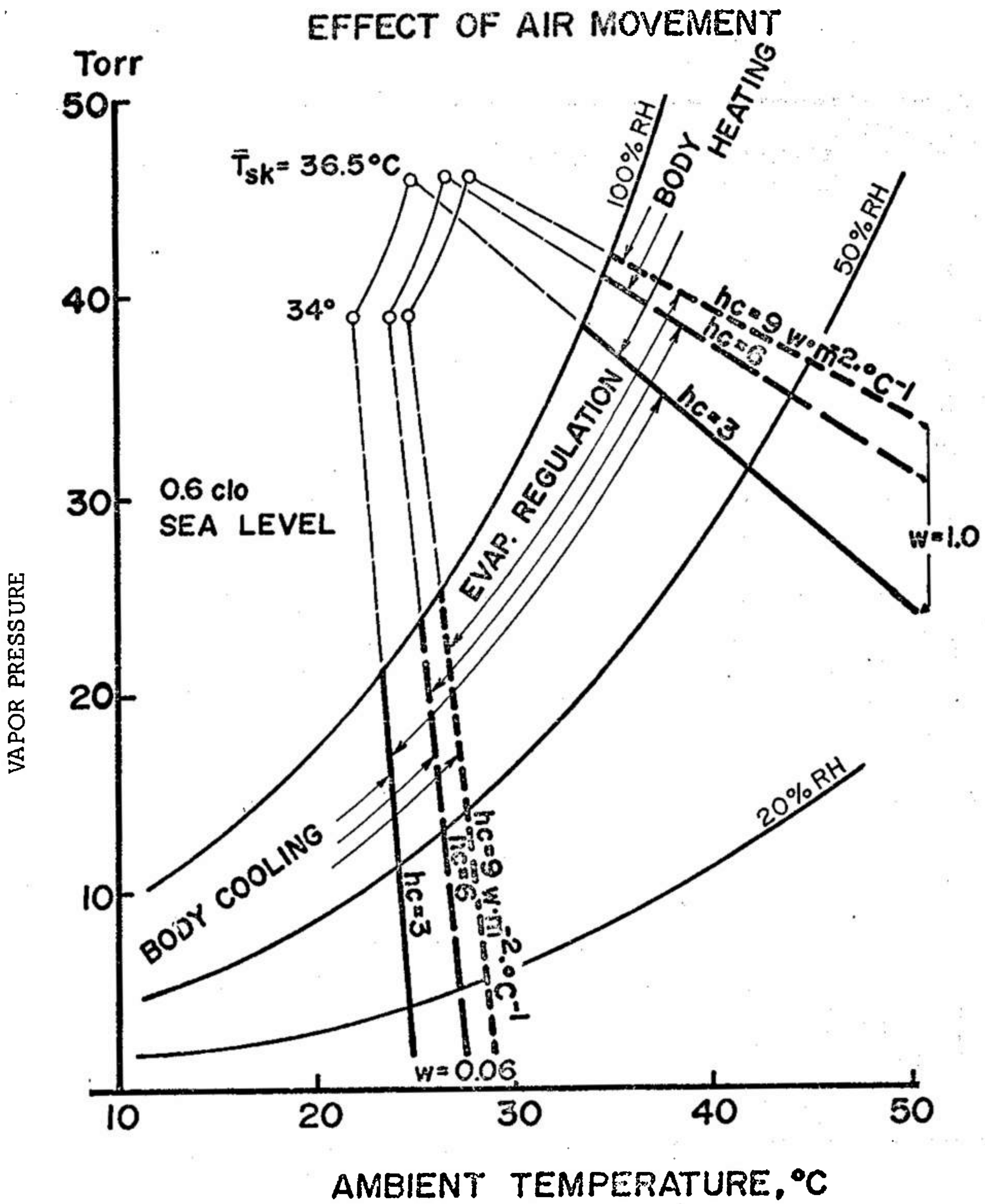

Figure 1. The effect of air movement on the zones for body heat exchange. At low temperatures increased air velocity cools the body faster and higher temperatures are needed to feel comfortable, while at higher temperatures increased windspeed allows the zone of evaporative regulation to be expanded. The convective heat coefficients 9, 6, and 3 are equivalent to air velocities of 1.1, 0.51, and .14 m/s, respectively.

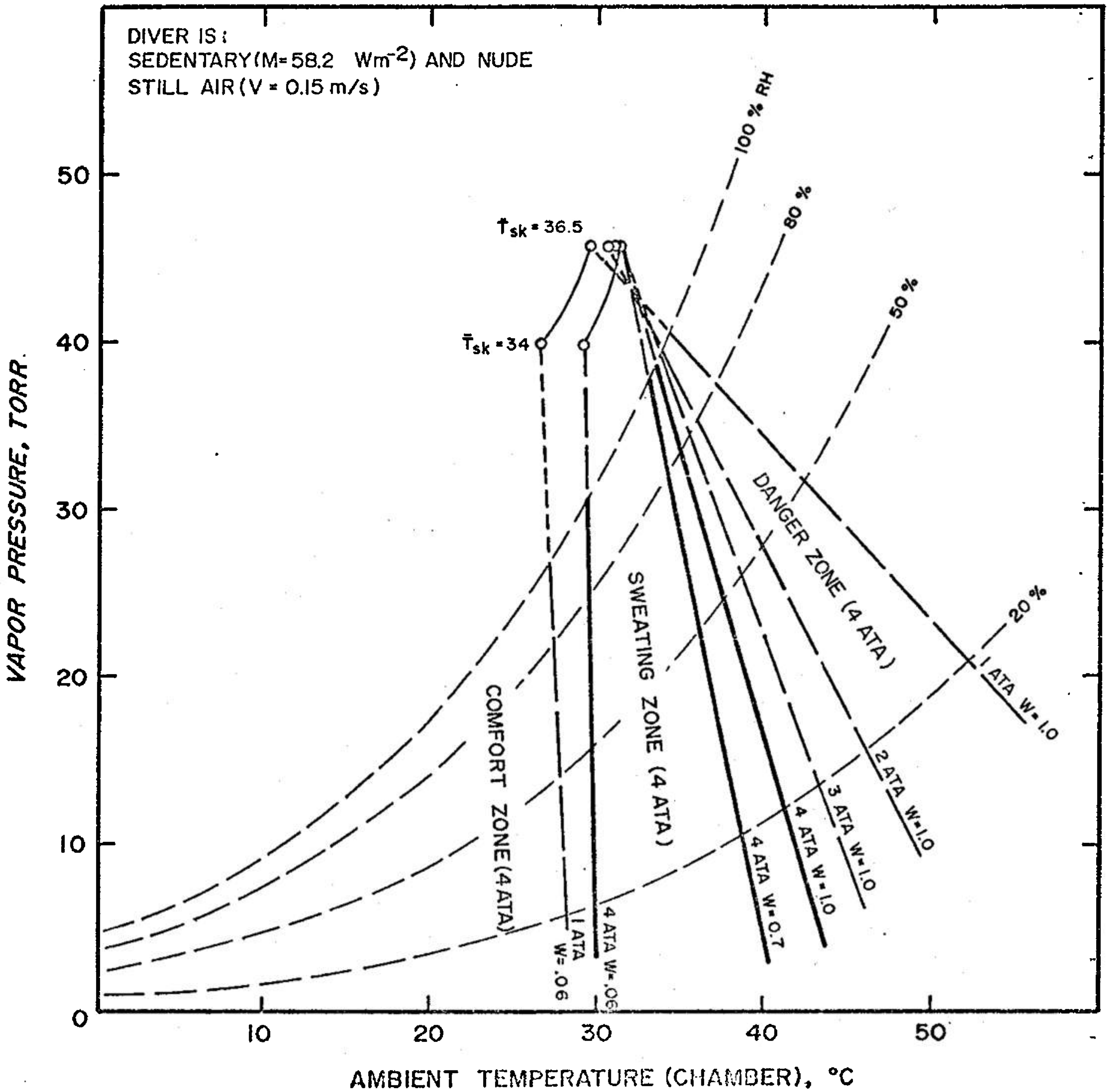

Figure 2. The effects of increased pressures on zones of body heat exchange. Note the progressive narrowing of the sweating zone or zone of evaporative regulation with increasing pressure.

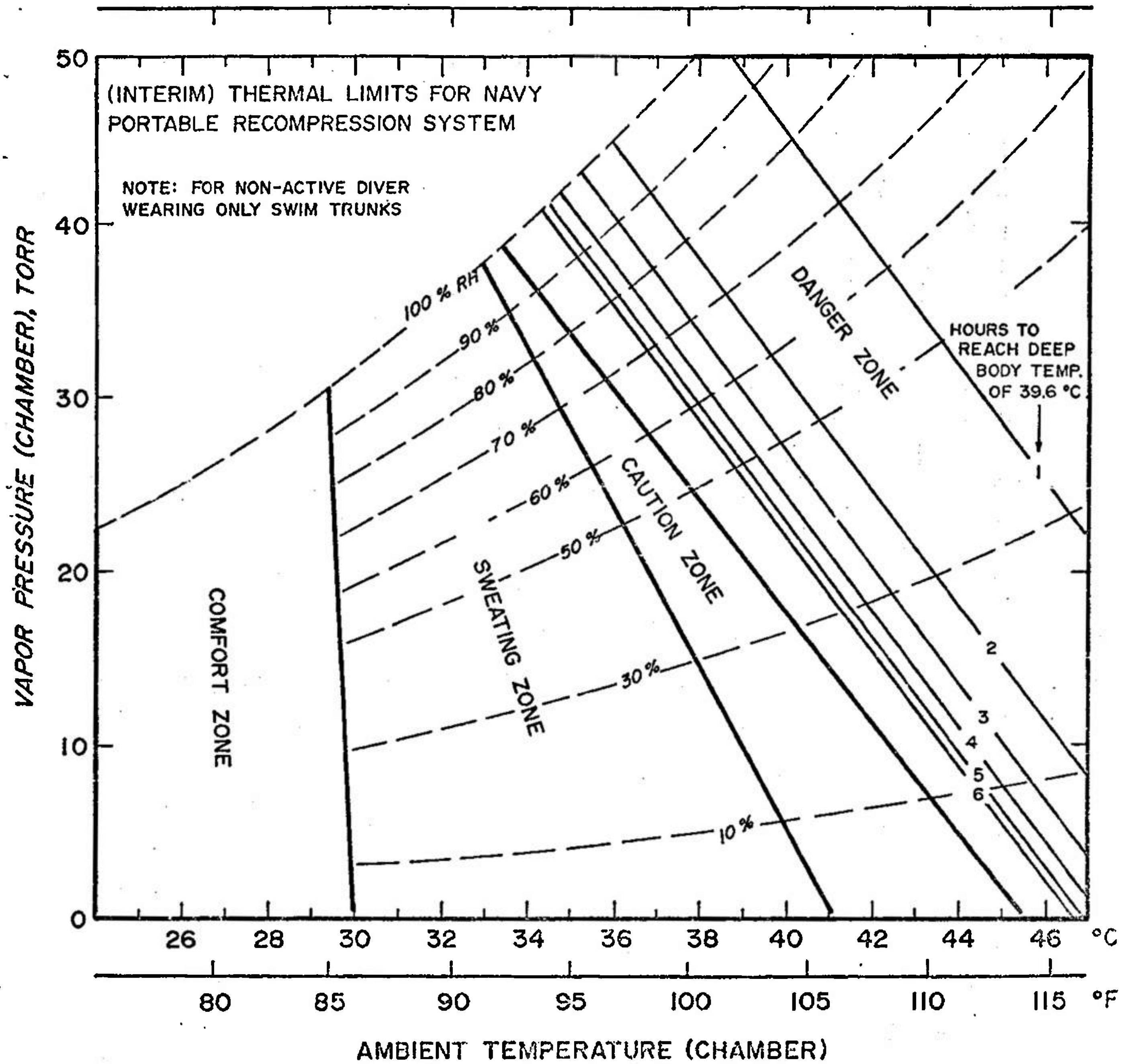

Figure 3. Skin wettedness lines of 0.06, 0.7, and 1.0 of figure 2 are replotted on an expanded X axis. "Hour Lines" to reach a deep body temperature of 39.6 are also plotted (see text and Appendix B for interpretations).

TABLE 1. Variables and Constants Used to Construct Zones of Heat Exchange on Psychrometric Charts

Parameter or Variable		ATA 1		ATA 2	ATA 3	ATA 4		
	w →	.06	1.0	1.0	1.0	0.6	.7	1.0
h_c [1]	$(Wm^{-2}\,{}^{o}C^{-1})$	3		4.4	5.5		6.4	
h_r [2]	(")	4.2	4.9	4.9	4.9	4.2	4.9	4.9
h_e	(")	6.6		4.8	4.0		3.5	
E_{res}	(Wm^{-2})	3.2		3.2	3.2		3.2	
C_{res}	(")	+0.8	-0.5	-1	-1.5	+0.8	-2	-2
$\bar{T}_{sk}$ [3]	(°C)	34	36.5	36.5	36.5	34	36.5	36.5
$P_{s,sk}$	(Torr)	39.9	45.8	45.8	45.8	39.9	45.8	45.8
M [4]	(Wm^{-2})	58.2	For All ATA and All w					
v [1]	(m/s)	0.15						
$clo^5 = 0$								
$T_o{}^6 = T_a = \bar{T}_r$	(°C)							

1 - 6, see Appendix A for remarks.

TABLE 2

Prediction of Final Deep Body Temperature for a Standard Man at Various Temperatures and Humidities, Accounting for Changing Treatment Depth and Stop Times.

T_a = 34.8; RH = 100% [1]	$\Delta T_b/\Delta h$	Stop Time [2] (min)	ΔT_b/stop (^oC)	Final [3] T_b (^oC)
Pressure at Stop 4	.66	44	0.5	37.5
3	.64	62	0.7	38.2
2	.60	92	0.9	39.1
1	.47	182	1.4	40.5
T_a = 35.6; RH = 90%				
4	.67	44	0.5	37.5
3	.60	62	0.6	38.1
2	.48	92	0.7	38.8
1	.20	182	0.6	39.4
T_a = 36.4; RH = 80%				
4	.66	44	0.5	37.5
3	.53	62	0.6	38.1
2	.32	92	0.5	38.6
1	0	182	0	38.6
T_a = 39.4; RH = 50%				
4	.64	44	0.5	37.5
3	.31	62	0.3	37.8
2	0	92	0	37.8
1	0	182	0	37.8

1. Temperature and humidity combinations were picked on the "4 hour" line for 4 ATA (thus, if total treatment was conducted at 4 ATA, T_b = 39.6 C at 4 hours).
2. Stop times were computed by grouping the following stops: (100 and 80) = 4 ATA; (60 and 50) = 3 ATA: (40 and 30) = 2 ATA; (20 and 10) = 1 ATA.
3. Initial T_b at start of treatment = 37.0

TABLE 3

OUTSIDE AIR TEMPERATURE (^{o}F)	HEAT STRESS EXPECTED
77 and below	The diver will not sweat and will feel comfortable. No changes in rectal temperature will occur and there should be no confounding effects of heat on decompression sickness.
78-84	Diver will sweat a little at the lower end of this zone and will feel uncomfortable and sweat profusely toward the higher ends of the zone. Heat load in this zone should be entirely compensable and should not affect treatment of decompression.
85	Diver will sweat profusely and be quite uncomfortable. Rectal temperature and heart rates are likely to rise but should reach a steady state. Heat load may confound the treatment of decompression. Water should be supplied for consumption at will. Must drink certain amount per time.
86-87	The diver, although sweating profusely, will not be able to compensate for the heat stress. Rectal temperature will continue to rise as long as the diver is subjected to these ambient conditions. The diver will have about 6 hours to complete collapse from heat stroke.
88 and above	At these temperatures the time to reach collapse is considerably shortened. Between 88-90, the time could be as short as 2 hours and at about 94 would be less than 1 hour.

APPENDIX A

Discussion of Remarks for Table 1 and Discussion of Assumptions Used in the Analysis

REMARK

1. A velocity of .15 m/s was chosen, but a velocity profile in the chamber has not been determined. Values of h_c were increased as a function of $(P_B)^{.55}$ and the initial value of 3 was chosen as a compromise (see Gagge, 9). Higher values might be created by the scrubber air blower, but this may be counteracted by the fact that the effective surface area for h_c to act upon may be decreased in the reclining diver.

2. h_r varies only with ambient temperature, which is different in this analysis for each level of wettedness.

3. Mean comfortable skin temperature was chosen to be 34°C and 36.5°C as the limit for thermoregulatory sweating, following closely the example of Nishi and Gagge (18). As T_a rises above the 40°C mark it is likely that $\bar{T}_{sk}$ will rise above 36.5, but for simplifying calculations $\bar{T}_{sk}$ was kept constant at 36.5°C. It is felt that this convention did not alter the analysis substantially.

4. A resting metabolism of 1 met (58.2 Wm^{-2}) was chosen as the diver will be expected to be reclining quietly, but should not be sufficiently relaxed to warrant a lower metabolic heat assignment.

5. The diver should be wearing swim trunks at most (clo = 0.05), but zero clo was chosen to greatly simplify calculations without sacrificing a great deal of accuracy.

6. T_o (operative temperature) may be defined as an average of T_a and $\bar{T}_r$ (mean radiant temperature) weighted by their respective governing heat transfer coefficients (9). It was assumed, for lack of real data, that chamber wall temperatures would be near or at ambient temperatures and that in warm environments may also be near mean skin temperature. Setting $T_o = T_a = \bar{T}_r$ is therefore justified.

Other Assumptions

A. "Standard Man". Throughout this analysis the DuBois surface area = 1.8 m^2 and mass = 70 kg, dimensions of what has been termed the "Standard Man". It has been shown however that the average Navy diver has a mass of 81 kg (1) and it may also be assumed that the divers' surface area is larger. While the diver will therefore be able to store more heat because of his mass he also produces more heat than the smaller man and therefore his rise in T_b should be smaller. The choice of the "standard man" should not affect the analysis to a significant degree.

B. <u>Healthy, Fit Young Divers</u>. Except for the illness for which they are being treated, the diver should be healthy, young, and fit. Wyndham (25) has shown that for men > 45 years or < 50 kg, tolerance to heat is greatly reduced.

C. <u>Humidity in the Chamber.</u> It is assumed that humidity levels in the chamber can be measured or estimated. Two laboratory PRS evaluation reports (15, 19) indicate that very high (90-100%) levels of humidity probably exist in the chamber. This is likely, since the man, through respiratory and evaporative losses will add water to the chamber continuously. Therefore, while humidity may in fact decrease upon compression with dry gas, it is likely that high levels will be obtained shortly thereafter.

APPENDIX B

ITERIM HEAT TOLERANCE LIMIT CHART FOR PRS CHAMBER

AMBIENT CONDITIONS INSIDE CHAMBER

Ambient conditions are defined as the temperature and humidity (or vapor pressure) of the chamber at 4 atmospheres absolute (100 FSW). To estimate these conditions before pressurization, add 5°C (9°F) to ambient air temperature to obtain chamber temperature. Relative humidity may be estimated to be 80-90% soon after depth is reached.

DETERMINATION OF ZONE FOR AMBIENT CONDITIONS

1. Locate ambient chamber temperature on the abscissa.
2. Move vertically upward to where the ambient chamber humidity is intercepted.
3. Until the danger zone is reached, the body should be able to compensate for any heat load for the duration of a 6-7 hour treatment. If point of interception is in the danger zone, estimate the time to reach a deep body temperature of 39.6°C (103.0°F) from the light diagonal hour lines.

INTERPRETATION OF ZONES

COMFORT ZONE: The diver will not sweat and will feel comfortable. No changes in rectal temperature will occur and there should be no confounding effects of heat on decompression sickness.

SWEATING ZONE: Diver will sweat a little at the lower end of this zone and will feel uncomfortable and sweat profusely toward the higher ends of the zone. Heat load in this zone should be entirely compensable and should not effect treatment of decompression.

CAUTION ZONE: Diver will sweat profusely and be quite uncomfortable. Rectal temperature and heart rate are likely to rise but should reach a steady state. Heat load may confound the treatment of decompression. Water should be supplied for consumption at will.

DANGER ZONE: The diver, although sweating profusely, will not be able to compensate for the heat stress. Rectal temperature will continue to rise as long as the diver is subjected to these ambient conditions. The time in hours to reach a deep body temperature of 39.6 is read from the chart. At this temperature the probability of total collapse from heat stroke is high. It is likely that the treatment for decompression sickness will be compromised by the heat stress.

NOTE: Use of this chart applies to divers who enter the chamber 1) nude or wearing only swim trunks, 2) and remain sedentary (non-active) and 3) in a normothermic state, i.e., show no signs of heat stress. If any of these conditions are not met, the various zones will occur at lower temperatures and humidities.

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER NSMRL Report 904	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Analysis of Interim Thermal Stress Limits for a Portable Recompression System		5. TYPE OF REPORT & PERIOD COVERED Interim
		6. PERFORMING ORG. REPORT NUMBER NSMRL Report 904
7. AUTHOR(s) Bondi, K. R.		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Naval Submarine Medical Research Laboratory Box 900, Naval Submarine Base New London Groton, Connecticut 06340		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Naval Medical Research & Development Command National Naval Medical Center Bethesda, Maryland 20014		12. REPORT DATE 7 August 1979
		13. NUMBER OF PAGES 14 + 2 appendices
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Thermal stress
Diving
Decompression sickness
Hyperthermia
Hyperbaric chamber
Life support systems

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

An analysis was conducted of the thermal heat loads expected and the diver's ability to regulate his internal temperature during use of the Navy's one-man portable recompression system (PRS). Using conventional heat balance and heat exchange relationships, a graph was constructed from which the heat load on the diver could be predicted knowing the ambient air temperature and humidity. Based on the assumption that relative humidity will be near 100% and introducing a safety margin by conducting the analysis as if the total decom-

pression treatment took place at 4 atmospheres absolute, the heat stress expected for various ambient air temperature is as follows: 25°C(77°F) and below - no heat stress expected, diver comfortable; 26-29°C(78-84°F) - diver will sweat profusely and be uncomfortable toward high end of zone, but stress should be entirely compensable; 29°C(85°F) - diver will be very uncomfortable and heart rate and rectal temperature will rise to a new steady state; 30-31°C (86-85°F) - diver unable to compensate for heat stress and rectal temperature and heart rate will rise continuously until collapse at about 6 hours; 31°C (88°F) and above - time to collapse is considerably shortened being 2 hours at 31-32°C(88-90°F) and less than 1 hour at 34°C(94°F).